Extraction of the sub-band gap density of states of Nb doped ZnO thin film transistors using C-V measurements

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C-V measurements were performed on NbZnO TFTs to extract the density of states by the multi-frequency method. The density of states demonstrates good agreement with extracted parameters from I-V measurements.

1. Introduction

Zinc oxide (ZnO) based materials for active layers in thin-film transistors (TFTs) have attracted considerable attention due to the high optical transparency (> 3.2 eV) for transparent electronics and relatively high electron mobility in comparison with a-Si:H. These disordered materials contain high concentrations of defects arising from interstitials and oxygen vacancies, which determine the conduction properties. There are a number of techniques to control these defects and enhance the electrical characteristics; commonly by doping the film with other metals such as Ga and In [1,2] or as demonstrated in our previous work, Nb [3] and Mg [4]. The extraction of the sub-band gap density of states (DOS) (g(E)) is a key parameter for characterising the ZnO film. A number of techniques have been reported for extracting the DOS and in this paper we will adopt the multi-frequency *C-V* method outlined by Lee *et al.* [5]. The DOS parameters obtained are compared with those extracted from *I-V* characteristics, which were analysed using the multi-trapping and release (MTR) model.

2. Experimental

The films were deposited using atomic layer deposition (ALD) on an oxidised Si wafer (50 nm SiO_2) with 5 nm of ALD Al_2O_3 to act as a capping layer, at 175 °C, using the precursors diethlyzinc and niobium pentaethoxide for ZnO and Nb respectively The cycle percentage for the Nb precursor was 12.5 %. Al source/drain (*S/D*) contacts were thermally evaporated and patterned using the lift-off process. Each device was isolated by wet etching the NbZnO and the films were annealed at 300 °C in air for 1 hour. Further details can be found in [3].

3. Results and Discussion

C-V measurements were conducted in parallel mode on 12.5 % NbZnO TFTs between the (*S/D*) and the back gate over a frequency (*f*) range of 100 to 100 kHz. Fig. 1 shows the *C-V* characteristics of the TFT with the substrate capacitance (C_{ox}) superimposed with symbols. It is evident there is a large frequency dispersion due to the high trap density in the film [6].

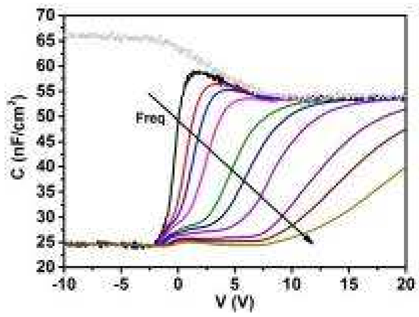

Fig. 1 Capacitance-voltage measurements for the substrate (symbols) and 175 °C 3.5 % NbZnO TFT (lines) for frequencies between 100 and 100 kHz

The equivalent circuit used is shown in Fig. 2(a-i). It can be transformed into the four-component model of Fig. 2(a-ii). The total impedance of the two-component model (Z_2) and four-component model (Z_4) are given by

$$Z_2 = \frac{R_m}{1+(\omega C_m R_m)^2} - j\frac{\omega C_m R_m^2}{1+(\omega C_m R_m)^2} \quad (1)$$

$$Z_4 = R_s + \frac{R_{ch}}{1+(\omega C_{ch} R_{ch})^2} - j\left(\frac{\omega C_{ch} R_{ch}}{1+(\omega C_{ch} R_{ch})^2} + \frac{1}{\omega C_{ox}}\right) \quad (2)$$

where $\omega = 2\pi f$, C_m and R_m are the measured capacitance and resistance respectively, R_s is the *f*-independent series resistance, C_{ch} and R_{ch} is the effective capacitance and resistance of the NbZnO channel. The extracted R_s is shown in Fig. 2(b) with the inset demonstrating the parameterisation technique for each applied voltage. By equating $Z_2 = Z_4$ the respective C_{ch} and R_{ch} can be calculated.

$$C_{ch} = \frac{bC_{ox}^2 - b^2 C_{ox}}{[(ab\omega)^2+1]C_{ox}^2 - 2bC_{ox} + b^2} \quad (3)$$

$$a = \frac{D_m}{\omega C_m(1+D_m^2)} - R_s,\ b = C_m(1+D_m^2) \text{ and } D_m = \frac{1}{\omega C_m R_m}$$

$$R_{ch} = \sqrt{\frac{C_m(1+D_m^2) - C_{ox}}{\omega^2 C_{ch}^2 C_{ox} - \omega^2 C_{ch} C_m (1+D_m^2)(C_{ch}+C_{ox})}} \quad (4)$$

The four-component model can be converted from the channel impedance (Z_{ch}) to the physics based model shown in Fig. 2(a-iii) accounting for the localised charge (Q_{loc}) a product of C_{loc} and R_{loc} and free charge (Q_{free}) dependent on C_{free}. Equating $Z_{ch} = Z_{phys}$ in (5) and (6) we obtain (7) to find R_{loc}.

$$Z_{ch} = \frac{R_{ch}}{1+(\omega C_{ch} R_{ch})^2} - j\frac{\omega C_{ch} R_{ch}^2}{1+(\omega C_{ch} R_{ch})^2} \quad (5)$$

$$Z_{phys} = \frac{C_{loc}^2 R_{loc}}{\omega^2 C_{loc}^2 R_{loc}^2 + (C_{loc}+C_{free})^2} - j\frac{\omega^2 C_{loc}^2 C_{free} R_{loc}^2 + (C_{loc}+C_{free})}{\omega^3 C_{loc}^2 C_{free}^2 R_{loc}^2 + \omega(C_{loc}+C_{free})^2} \quad (6)$$

$$R_{loc} = \sqrt{\frac{\omega^2 C_{ch} R_{ch}^2 (C_{loc}+C_{free})(C_{loc}+C_{free}-C_{ch}) - (C_{loc}+C_{free})}{\omega^2 C_{loc}^2 C_{free}[1+\omega^2 C_{ch} R_{ch}^2 (C_{ch}-C_{free})]}} \quad (7)$$

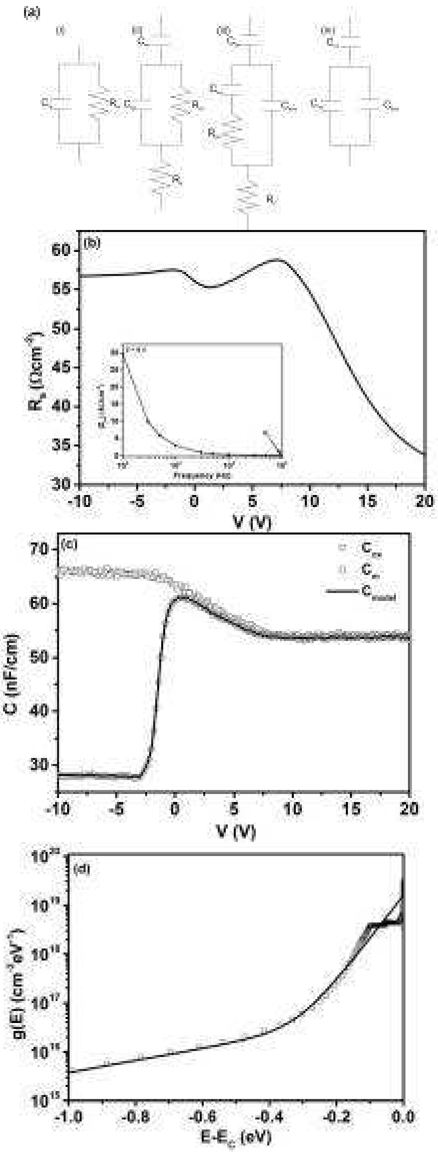

Fig. 2(a) i. two-component capacitance model ii. four-component capacitance model, iii. physics based capacitance model, iv. frequency independent capacitance model (b) extracted voltage dependent R_s (inset) extraction technique, (c) frequency independent C-V characteristics extracted from three frequencies ($f_{1\text{-}3}$=100,10 k and 100 kHz) and (d) the extracted sub-band gap DOS with Equation (11) superimposed

As C_{loc}, C_{free} and R_{loc} are *f*-independent; they are obtained by equating for three frequencies, $R_{loc}(\omega_1)= R_{loc}(\omega_2)= R_{loc}(\omega_3)$. The *f*-independent parameter model is shown in Fig. 2(a-iv) and the characteristics in Fig. 2(b). The voltage dependent Q_{loc} is obtained through C_{loc}, hence the DOS can be estimated by

$$C'_{loc} = \frac{[C_{loc}(V_1) - C_{loc}(V_2)]}{WL} \quad (8)$$

$$g(E) = \frac{C'_{loc}}{q^2} \quad (9)$$

To obtain the relationship between the applied voltage and energy from the conduction band (surface potential, ϕ_s), the *f*-independent *C-V* from Fig. 2(c) is integrated over the applied voltage.

$$\phi_s = \int_{V_{FB}}^{V} \left(1 - \frac{C}{C_{ox}}\right) dV \quad (10)$$

The extracted *g(E)* is shown in Fig. 2(d) with the two term exponential DOS model superimposed to account for the tail and deep states given as

$$g(E) = N_{tail}\exp\left(-E_C - E/kT_{tail}\right) + N_{deep}\exp\left(-E_C - E/kT_{deep}\right) \quad (11)$$

where the extracted model parameters for (11) are N_{tail} =1.6 × 10^{19} cm^{-3}, T_{tail} =540 K (49 meV), N_{deep} = 6.5 × 10^{16} cm^{-3} and T_{deep} = 4058 K (350 meV). By comparison with the *I-V* fits from the MTR model [3] given in Fig. 3, T_o = 540 k (49 meV) N_t = 3.8 × 10^{19} cm^{-3}. There is good agreement with the number of trapping states near the conduction band (N_t ~ N_{tail}) and the characteristic temperatures (T_o ~ T_{tail}), demonstrating the dominance of the tail states on the conduction mechanism.

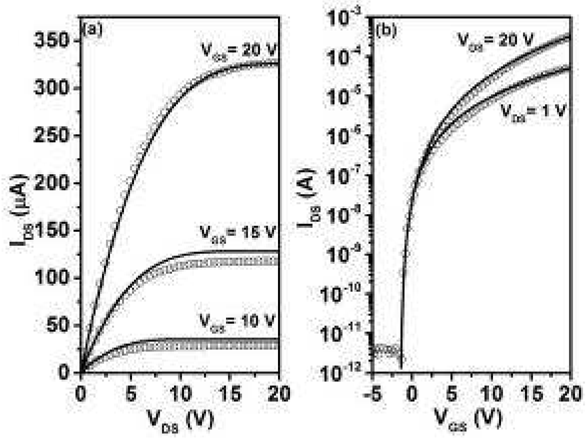

Fig. 3 Fitted (a) output characteristics and (b) transfer characteristics of NbZnO TFT using the MTR model [3]

4. Conclusion

C-V measurements were conducted on NbZnO TFTs over a frequency range of 100 to 100 kHz. The DOS was extracted using the multi-frequency method. There is good agreement with the tail states fittings from the *C-V* and *I-V* measurements using the MTR model.

References

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